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The Effect of Two Sock Fabrics on Perception and Physiological Parameters Associated with Blister Incidence: A Field Study

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The goal of the present study was to investigate differences in perception and skin hydration at the foot of two sock fabrics with distinct moisture properties in a realistic military setting. Thirty-seven military recruits wore two different socks (PP: 99.6% polypropylene and 0.4% elastane, and BLEND: 50% Merino-wool, 33% polypropylene, and 17% polyamide), one on each foot. Measurements were carried out after a daily 6.5-km march on 4 days. Each participant rated temperature, dampness, friction, and comfort for each foot. On a daily selection of participants, skin hydration was measured on three sites of both feet using a corneometer, and moisture content of the socks was determined. BLEND was rated to be cooler, less damp, and more comfortable ($P < 0.05$). Two out of three skin sites were drier for BLEND than PP ($P < 0.05$). Moreover, BLEND stored 2.9 ± 0.3 times more moisture compared to PP. Thus, under the present conditions, socks such as BLEND are to be preferred over polypropylene socks.

Keywords: blister; comfort; footwear; hiking; marching; polypropylene; skin hydration; sock; wool

INTRODUCTION

Hiking is associated with incidence of friction blisters on the foot. In fact, for recreational long-distance hikers, blister incidence ranges from 7 to 50% based on questionnaires (Crouse and Josephs, 1993; Twombly and Schussman, 1995; Gardner and Hill, 2002). However, blisters also manifest in an occupational setting, such as in the army. Blister incidence in soldiers can be as high as 45% during a typical single- or multiday march (Knapik *et al.*, 1992, 1997; Reynolds *et al.*, 1999). Moreover, for such marches, blisters result in limited duty time of 30.6 days per 100 recruits during a 12-week training program (Knapik *et al.*, 1996) or 5.4 days per 100 soldiers following 20-km road march while carrying 46 kg total load (Knapik *et al.*, 1992).

Under typical hiking conditions, blisters are caused by friction between the skin of the foot and the sock. It has been established that such friction increases with increasing moisture content of the skin (Sulzberger *et al.*, 1966; Nacht *et al.*, 1981; Elsner *et al.*, 1990; Kenins, 1994; Gerhardt *et al.*, 2008) and fabric (Gwosdow *et al.*, 1986). Since fabrics cope with moisture differently (e.g. Rossi *et al.*, 2011), several groups have investigated the effect of sock fabric on blister incidence. Herring and Richie (1990) indicated that in marathon runners, acrylic socks result in a significantly lower blister incidence compared to cotton socks. Two other studies followed large numbers ($n > 180$) of military recruits during periods of 6 weeks (Van Tiggelen *et al.*,

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2009) or 12 weeks (Knapik *et al.*, 1996) and reported that blister incidence was lower if socks did not have wool or cotton in direct contact with the skin.

In order to get a better understanding of the underlying mechanisms of how different fabrics contribute to blister incidence, a series of studies were carried out in our laboratory. First, moisture transport behavior of different sock fabrics was evaluated using X-ray tomography (Rossi *et al.*, 2011). Polypropylene was among the fabrics transporting moisture away from the simulated skin under 81 kPa. Reduced moisture at the skin is likely to reduce the coefficient of friction and therefore the risk of blisters. A wool/polyamide blend was found to have the largest moisture absorption capacity, although it performed poorly with regards to transporting water away from the simulated skin. In a second study, 12 participants underwent three 30-min walking sessions on a treadmill with two different types of socks: a 99.6% polypropylene and 0.4% elastane sock, and 50% Merino-wool, 33% polypropylene, and 17% polyamide sock (Bogerd *et al.*, 2011). The results indicated no significant differences on skin hydration and skin friction of the foot between both sock fabrics. These results indicate that no differences in blister incidence between both sock fabrics are to be expected under these laboratory conditions. However, 30 min might be too short for differences between polypropylene socks and wool blend socks to manifest. Therefore, the aim of the present study was to quantify skin hydration and moisture absorption in two different types of sock fabrics in boots, as well as perceptions of temperature, dampness, friction, and comfort, during multiple hours of military training.

METHODS

Participants

A group of 37 military recruits participated in this study, lasting four consecutive days. However, the number of participants fluctuated between 32 and 37 over the measuring period due to absences caused by illness, injury, or other (private) reasons. Table 1 represents these daily fluctuations. The participants were in their eighth week of basic military training and wore standard marching clothing for neutral conditions, referred to as ensemble C (or CNK 420) in the Swiss Army. In brief, this ensemble consisted of underwear (100% polyester), a long-sleeved shirt (cotton/polyester blend), long pants (cotton/polyester blend), a backpack, a rifle, and waist packs. The total weight of the ensemble was 22 kg. During the measuring period, all participants wore a prototype military boot equipped with a GORE TEX membrane. The boots were new and not used until the first measuring day. The study was carried out from a military base in Aarau, Switzerland.

Intervention

The two sock types were fabricated from different fabric, but for a given sock, the fabric was constant for the entire sock and constructed using a plush knit (Jacob Rohner AG, Balgach, Switzerland). One such sock consisted of polypropylene (PP: 99.6% polypropylene and 0.4% elastane) and another sock was made from a wool blend (BLEND: 50% Merino-wool, 33% polypropylene, and 17% polyamide). These two fabrics were found to have distinctively different moisture properties (Rossi *et al.*, 2011); PP transported moisture away from the simulated skin under 81 kPa pressure, whereas a wool/polyamide blend was found to have the largest moisture absorption capacity (Rossi *et al.*, 2011). BLEND used in the present study was slightly different from that study in order to improve wearability. Besides the fabric, all other factors, e.g. thickness and shape, were kept as constant as possible between BLEND and PP. The socks employed in the present study were similar to the socks used in our recent laboratory study (Bogerd *et al.*, 2011). The two sock types were differently color coded by a 1-cm-thick band at the proximal part of the sock, allowing easy identification by the participants and the experimenters. The participants were not instructed about the difference between the sock types. Five sock sizes were available, corresponding to the following foot lengths (millimeters): 230–245, 250–260, 265–275, 280–290, and 300–310. All socks underwent

Table 1. Total number of participants per group per day and number of participants undergoing additional measurements.

Group	Sock type[a]		Number of participants per day				Numbers of participants with additional measures per day			
	L	R	1	2	3	4	1	2	3	4
1	BLEND	PP	18	20	18	17	1	6	5	5
2	PP	BLEND	17	17	17	15	3	4	3	1
Total			35	37	35	32	4	10	8	6

[a]More details about the sock types are given in the text.

one standard industrial washing cycle after delivery from the manufacturer.

Protocol

Each participant wore two different socks, allowing a direct within-participant comparison of the different sock types. Each day, a participant wore new socks but always the same sock type on the same foot. The participants were randomly divided into two subgroups, wearing BLEND and PP, respectively, left and right (A) or right and left (B) (Table 1). Each morning it was verified that each participant wore the sock type on the correct foot. The participants were instructed not to take off the boots and socks from this check until after the measurements on the same day.

The participants underwent basic military training, including theoretical instructions and drill exercises in the field, and marched during the latter part of the afternoon and beginning of the evening. This march ended on the military base and started elsewhere, at fixed location. The march consisted of a 6.5-km horizontal distance, with a total of 145 m ascending and 214 m descending, approximately one half on dirt roads and one half on asphalt roads, and was completed in 60–70 min. The ensemble described under Participants section, totaling 22 kg, was worn during the march. The air temperature (T_a) and relative humidity (RH) were measured using a meteorological station (SensoTCMod 5507, Sensor Electronic, Gliwice, Poland). These parameters were recorded only during the march, every minute; the station was positioned on the military base. Precipitation was obtained from an official weather station of the Swiss Federal Office of Meteorology and Climatology having the shortest distance to the marching area.

Measurements

Measurements were carried out subsequent to each march. All participants started by filling out a questionnaire concerning the socks. On a selection of 4–10 participants, additional measurements were carried out daily (Table 1). The number of participants per day fluctuated because of an additional sock condition, which cannot be reported in the present manuscript due to confidentiality. The selection was made randomly and no participant was measured more than once. These additional measurements included skin hydration and sweat absorption of the socks, which are detailed below.

The perception of all participants on both socks was daily evaluated after the march, using visual analog scales (VAS) with which the following parameters were rated: (i) temperature, (ii) dampness, (iii) skin friction, and (iv) comfort. Each VAS consisted of a horizontal, 10-cm-long line. On both ends of the line, both extreme answers were given, e.g. for temperature very cold and very hot. Such analog or continuous scales have been used before for assessing similar perceptual parameters (Nunneley *et al.*, 1982; Zhang *et al.*, 2004; Cotter and Taylor, 2005; Arens *et al.*, 2006). For each question, two VAS were provided on one sheet allowing direct comparison between the ratings for both feet. The questionnaires were available in the native language of the participants (German or French).

Skin hydration was measured after the questionnaire was completed, for the selected participants who underwent additional measurements. These measurements were similar to our recent laboratory study (Bogerd *et al.*, 2011), using a corneometer (CM 825, Courage & Khazaka, Cologne, Germany). The following sites were evaluated: (i) the plantar surface of the distal phalanx of the first digit (sole of the great toe), (ii) the posterior surface of the calcaneus (rear of heel), and (iii) the dorsal surface of the third metatarsal (upper side of the center of the foot). The former two were selected since blisters often occur on these sites. The latter represents an area of low pressure, which allows us to compare the present results with a study evaluating the moisture behavior of sock fabrics at two different pressures (Rossi *et al.*, 2011). Three similar measurements, on hairless skin, were made from each site and the average value was used for statistical analysis. The corneometer derives the skin hydration from measurements of the electrical capacity at the skin, which is a function of skin hydration (Fluhr *et al.*, 1999) and given in arbitrary units. Ambient conditions of the room were $T_a = 21.0 \pm 0.8$°C and RH $= 50 \pm 6$% (MSR14, MSR, Henggart, Switzerland).

The weight of the socks was determined directly after the participant took off the boots and socks, using a scale (SB16001, Mettler Toledo, Im Langacher, Switzerland). These measurements were carried out parallel to skin hydration measurements for all participants who underwent additional measurements. Subsequently, the socks were dried overnight to determine the absorbed moisture (expressed as milligrams per gram sock, to normalize for size differences).

Two weeks before the study took place, age and several anthropometrical parameters of all participants were registered. During this pre-session, each participant reported their age, followed by measurements of their body mass (ID5 Multirange, Mettler, Albstadt, Germany), and body height using standard measuring tape, the latter two according to ISO8559 (1989). Finally, the nude length of each foot of each participant was measured using a foot scanner (Inform/F1, ENVISIBLE/TU Chemnitz, Chemnitz, Germany). This measure was used for selecting the socks and to provide a start point for finding the properly fitting boot. The scanning technology used for determining the foot shape is based on 2D photography. One camera for each foot was used to image the plantar view of the foot. The plantar foot shape was then digitally processed. The foot length was defined as the maximum distance from the rear of the heel to the tip of the longest toe, measured parallel to the longitudinal axis of the foot. The longitudinal axis paralleled a line running through the medial most part of the front of the foot and the medial most part of the rear of the foot. The accuracy of this method is ±1.4 mm.

Data processing and statistics

The distribution for each parameter was determined using a Shapiro–Wilk test, indicating that all data were Gaussian distributed. A *t*-test was employed to compare the anthropometrical parameters between groups A and B. All meteorological parameters were tested using analysis of variance (ANOVA) repeated measures, and a Bonferroni-corrected *t*-test was used for post hoc comparison if the threshold for statistical significance ($P < 0.05$) was reached.

Perception (VAS scores), skin hydration, and moisture absorption were analyzed using ANOVA repeated measures. Group (A or B) and day (1 through 4) were given as between-participant factors, in order to investigate a foot-specific effect and a time effect. A Bonferroni-corrected *t*-test was used for post hoc comparison if significance was reached. Only data from participants for whom a complete dataset was available were evaluated. In order to test differences between the sock fabrics, the weight of each sock type was measured for 10 samples for each size after washing and before they were distributed to the participants. A *t*-test was used for statistical evaluation of the weight of the new socks.

Pearson's correlation coefficients were obtained for all possible combinations of perception (VAS scores), skin hydration at all three sites, and moisture absorption. All tests were carried out using SPSS 19.0 and the data processing was carried out using Matlab 7.11 (R2010b). Values are presented as mean ± SD.

RESULTS

General

The average anthropometrical characteristics of the participants were as follows: age 20.8 ± 2.0 years, weight 76.3 ± 9.8 kg, height 178 ± 7 cm, and foot length 271 ± 11 mm. Both groups did not differ in terms of anthropometrical parameters. Most days showed differences among the measured meteorological parameters (Table 2). No foot-specific effect was found for any parameter in the analysis given below. Therefore, the data of groups A and B were pooled. The weight of both sock types was similar for sizes 1–4, but PP was 0.65 ± 0.56 g heavier than BLEND ($P = 0.002$) for size 5.

Questionnaire

Intervention effects were found for temperature ($P = 0.019$), dampness ($P = 0.002$), friction ($P = 0.045$), and comfort ($P = 0.008$) (Fig. 1). Moreover, compared to PP, BLEND was perceived as cooler, less damp, with less friction, and more comfortable. A time effect was found for perception of temperature ($P = 0.006$) indicating perception of warmer feet on day 1 compared to day 2 ($P = 0.040$) and day 1 compared to day 3 ($P = 0.010$). Also dampness showed a time effect ($P = 0.001$) with more damp perception on the last day compared to the first day ($P = 0.004$). In addition, an intervention effect between measuring day and perception was found for comfort ($P = 0.030$).

Skin hydration

The measuring day did not affect skin hydration ($P = 0.893$), so the pooled values are presented in Fig. 2. The posterior surface of the calcaneus (BLEND–PP = −13%) and the dorsal surface of the third metatarsal (−8%) showed differences between PP and BLEND ($P = 0.023$ and $P = 0.003$,

Table 2. Meteorological conditions as measured during the march.

	Day				Significant difference[a]	Average
	1	2	3	4		
Air temperature (°C)	13.7 ± 0.7	11.5 ± 0.1	8.6 ± 0.1	8.5 ± 0.2	$P < 0.001$	10.6 ± 2.2
Humidity (%)	57.0 ± 1.5	79.8 ± 0.5	88.4 ± 0.8	77.1 ± 1.9	$P < 0.001$	75.6 ± 11.5
Precipitation (total) (mm)	0.3	0	2.7	1.1	$P < 0.001$	1.0

[a] *P* values obtained from ANOVA analysis; post hoc analysis indicated that most days are different from each other.

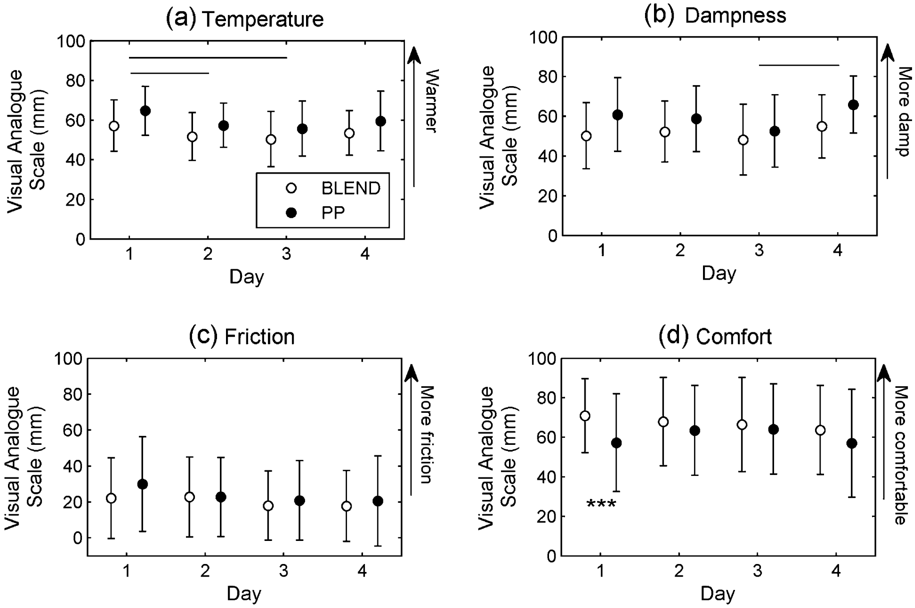

Fig. 1. Results from the VAS for each day, for PP (closed circles) and BLEND (open circles), given for (a) temperature, (b) dampness, (c) friction, and (d) comfort. Time effects are indicated with lines, where the days corresponding to the ends of the line are different in the time domain. Interaction effects are indicated with an asterisk; ***$P < 0.001$. Values are presented as mean ± SD.

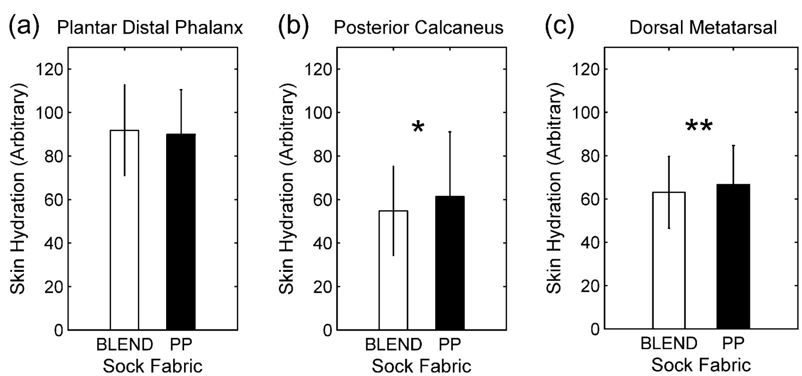

Fig. 2. Skin hydration for both sock fabrics for the following locations: (a) the plantar surface of the distal phalanx of the first digit (sole of the great toe), (b) the posterior surface of the calcaneus (rear of the heel), and (c) the dorsal surface of the third metatarsal (upper side of the center of the foot). Significant differences between PP and BLEND are given as *$P < 0.05$ and **$P < 0.01$. Values are presented as mean ± SD.

respectively), whereas no differences were found for the plantar surface of the distal phalanx of the first digit ($P = 0.655$).

Moisture absorption

The moisture absorption was independent from the day of measurement ($P = 0.768$), so the pooled values are presented in Fig. 3. BLEND absorbed 2.9 ± 1.3 times more moisture compared to PP ($P = 0.001$). For instance, the middle size sock PP absorbed 3.3 ± 1.7 g, whereas 6.0 ± 2.6 g was absorbed for the same size BLEND. This sock size resulted in a factor of 3.2 ± 1.6 more moisture absorbed by BLEND, if first for each single participant the factors are calculated, after which the average factor is obtained.

Correlations

All parameters showed a significant correlation between both feet, for any given parameter ($r = 0.75 \pm 0.15$, $P < 0.017$). Additional correlations were found for perception of temperature for BLEND with dampness for both BLEND ($r = 0.48$, $P = 0.011$) and PP

($r = 0.39$, $P = 0.038$). Skin hydration of all three sites and moisture absorption also showed addition correlations (Table 3), indicating relationships between most of these parameters ($r = 0.52 \pm 0.18$). The most systematic exception was the lack of a correlation for skin hydration between the plantar distal phalanx and the dorsal metatarsal.

DISCUSSION

The present results indicate improved skin hydration in socks consisting of a blend of wool/polypropylene/polyamide (BLEND) compared to socks mainly made of polypropylene (PP) after several hours of use in a military setting, for two skin sites: (i) the posterior surface of the calcaneus and (ii) the dorsal surface of the third metatarsal. The differences in skin hydration levels are probably explained by the distinct differences between both fabrics in moisture transport behavior (Rossi *et al.*, 2011). No significant correlations were found between any given perceptual parameters and skin hydration or moisture absorption under the present conditions, indicating that these parameters have little or no influence on each other. The significant relationship for a given parameter between a site and its contralateral counterpart expresses the participant's sensitivity level for a perceptual parameter or personal variations in sweat rate and skin hydration characteristics for the remaining parameters.

A previous study focusing on marathon runners reported reduced blister incidence for acrylic socks compared to cotton (Herring and Richie, 1990). Since acrylic fabric is hydrophobic and cotton hygroscopic, their moisture transport behavior is expected to be partly similar to PP and BLEND, respectively. Based on these results, one might expect PP to result in a dryer skin hydration compared to BLEND. However, the considerable differences in shoes/boots between runners and soldiers need to be taken into consideration. The former have very open shoes posing a much smaller water vapor resistance compared to the latter. This suggests that under conditions similar to the field study, moisture absorption plays a key role, considering typical military boots. Reported sweating levels of the foot range from 381 to 447 g m^{-2} h^{-1}, for exercise under warm conditions (Taylor *et al.*, 2006; Fogarty *et al.*, 2007; Bogerd *et al.*, 2011). We hypothesize that for military boots, the level of water vapor resistance results in an accumulation of moisture in the footwear at least at the sweat production peaks. This suggestion is supported by the finding that 2.9 ± 0.3 times more moisture is absorbed by BLEND compared to PP, coinciding with a dryer skin for BLEND, for two out of three skin sites. Thus, a BLEND sock absorbing excessive moisture that cannot be evacuated because of the resistance to water vapor might be a better choice for a military boot. Unpublished measurements from our laboratory indicated that water vapor resistance might be lower for similar military boots

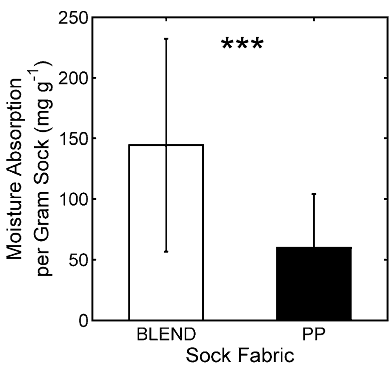

Fig. 3. Moisture absorption of the different sock fabrics. The moisture absorbed was expressed as milligrams per gram sock, to normalize for sock size. ***$P < 0.001$. Values are presented as mean ± SD.

Table 3. Pearson's correlation coefficients (r) between different parameters.

			Skin hydration						Moisture absorption	
			(a) Plantar distal phalanx		(b) Posterior calcaneus		(c) Dorsal metatarsal			
			BLEND	PP	BLEND	PP	BLEND	PP	BLEND	PP
Moisture absorption		PP	**0.52**	0.33	**0.71**	**0.67**	**0.64**	**0.45**	**0.86**	
		BLEND	**0.46**	**0.39**	**0.75**	**0.59**	**0.80**	**0.58**		**0.86**
Skin hydration	(c)	PP	0.28	0.33	**0.49**	**0.52**	**0.78**		**0.58**	**0.45**
		BLEND	0.28	0.22	**0.59**	**0.43**		**0.78**	**0.80**	**0.64**
	(b)	PP	**0.38**	**0.51**	**0.80**		**0.43**	**0.52**	**0.59**	**0.67**
		BLEND	**0.40**	0.36		**0.80**	**0.59**	**0.49**	**0.75**	**0.71**
	(a)	PP	**0.45**		0.36	**0.51**	0.22	0.33	**0.39**	0.33
		BLEND		**0.45**	**0.40**	**0.38**	0.28	0.28	**0.46**	**0.52**

Significant correlations ($P < 0.05$) are given in bold.

without laminate. It is unlikely that the water transmission rates are higher than the typical sweat rates reported above. However, these speculations need to be verified by empirical measurements.

One of the three sites where skin hydration was measured (sole of great toe) was not different in both socks. This site likely experienced larger pressures compared to the top of the foot. X-ray tomography indicated that under low pressure (0.4 kPa), the differences between moisture stored close to the simulated skin were 1.5 times larger for a wool fabric compared to a polypropylene fabric (Rossi *et al.*, 2011). For the site where a difference in skin hydration was found, this indicates that the differences were likely caused by the larger capacity of BLEND to store moisture. However, under higher pressure (81 kPa), the moisture storage close to the skin was ~3 times larger for a 100% wool fabric compared to a 100% polypropylene fabric (Rossi *et al.*, 2011). In the present study, the hydration of the sole of the toe was not different between socks, suggesting that the superior moisture storage of BLEND is reduced due to fabric compression, and/or the duration that PP benefits from the superior moisture transport is shorter than a state of complete saturation of the fabric. However, it must be noted that under realistic conditions, the pressures in a boot are dynamic, fluctuating with the gait cycle. Finally, BLEND employed in the present study contained 50% wool, whereas Rossi *et al.* (2011) used a 100% wool sock. Thus, comparisons between both studies are indicative only. However, although our previous study (Rossi *et al.*, 2011) used socks with 100% wool, unpublished results showed that wool strongly influences the moisture management behavior in a blend fabric.

These results give a more in-depth interpretation on blister incidence in military field studies (Knapik *et al.*, 1996; Van Tiggelen *et al.*, 2009). These authors reported reduced blister incidence for socks in which wool or cotton is not in direct contact with the skin. The present results indicate that a wool blend was more favorable than PP, thereby making it less likely that the absence of wool explains the results reported by the Knapik *et al.* (1996) and Van Tiggelen *et al.* (2009). It remains unclear if there is a common parameter in the previous two and the present study which explains most of the improvement.

The meteorological conditions were different among most days (Table 3). For instance, different levels of rain were observed. Since boots were equipped with a GORE TEX membrane for waterproofing, it is unlikely that a substantial amount of water entered the boots through the material of the boot. In addition, no time effects were found for skin hydration and moisture absorption, suggesting that the meteorological conditions did not affect the socks. Finally, ambient temperature, RH, and precipitation did not have a significant effect on any of the measured parameter. This was indicated by the lack of Pearson's correlations and no significant effect of these parameters evaluated as between-participant factors in the ANOVA repeated measures.

The socks showed indistinguishable weight between fabrics for a given size before use, with the exception of the largest size. It is unlikely that the difference for the largest sock size explains some of the variance of the reported results. First, the differences of 0.65 ± 0.56 g amounts to 1.5% of the absolute weight of both BLEND and PP. Second, only 2 out of the 28 participants for which the sock weight was determined wore size 5. In addition, over the course of sock use, some characteristics other than the moisture absorption likely changed, e.g. sock thickness and softness. However, such parameters were not measured in the present study.

OUTLOOK

Wool usually does not rank among the fabrics with the lowest friction (Bertaux *et al.*, 2007). Thus, reducing friction of wool might further improve military/hiking socks, as long as other relevant properties are not negatively affected, e.g. moisture absorbency and moisture transporting properties. Potentially, such improvements could be yielded by application of coatings (Bertaux *et al.*, 2009) or modifying fabric knit (Baussan *et al.*, 2010). Water vapor resistance of military/hiking boots remains undetermined, but further studies using foot manikins (Bergquist and Holmér, 1997; Kuklane and Holmér, 1998; Schols *et al.*, 2004; Babič *et al.*, 2008) are needed to test the hypothesis that the increased water vapor resistance for military boots allows for a sufficient moisture absorption capacity to store sweat at least at the sweat production peaks. The boots used in the present study were new. Thus, the fit of the boots might have changed over time (worn in). Since pressure interacts with fabrics with regards to moisture management, future studies could focus on the effect of different boots resulting in different pressure distributions on moisture management of sock fabrics.

CONCLUSIONS

The present results indicate differences between two sock fabrics: a wool blend (BLEND) and polypropylene (PP). Compared to PP, BLEND was rated to be cooler, less damp, and more comfortable. BLEND was found to store a factor 2.9 ± 0.3 more moisture compared to PP. Two out of three skin sites were found to be different between both fabrics, with dryer skin for BLEND measured on (i) the posterior surface of the calcaneus and (ii) the dorsal surface of the third metatarsal. No differences between BLEND and PP were found for skin hydration of the plantar surface of the distal phalanx of the first digit. Thus, under the present conditions, a benefit is found for BLEND over PP, especially for the sock regions other than the sole.

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